Nuclear structure investigations of heavy actinide and trans-actinide isotopes

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Introduction

Approximately 35 years ago the search for superheavy elements (SHE) was initiated by extrapolations of the nuclear shell model into regions far above the heaviest nuclei (Z=103) known at that time. The next (spherical) closed proton and neutron shells above the doubly magic nucleus ^{208}Pb were predicted at Z=114 and N=184 [1]. A large number of new nuclides having Z > 100 was identified since then, but for most of them only some basic decay properties could be measured due to low production rates. Significant enhancement of the experimental sensitivity during the past years now allows detailed decay studies for numerous isotopes up to Z=108. Those results deliver valuable information on the nuclear structure of these nuclei or their decay products, thus forming a framework for further developments of enhanced theoretical predictions of properties of still unknown superheavy nuclides.

Experimental Procedure

Information on the structure of transfermium nuclei can be obtained so far as well by decay spectroscopy as by in-beam spectroscopy. In the latter case detectors suited to measure radiation (γ-rays, conversion electrons(CE)) emitted during the deexcitation process of the compound nucleus are placed close to the target position. It delivers information on nuclear levels populated during the deexcitation process after particle emission, i.e. information on the structure of the evaporation residue (ER). In-beam spectroscopy of transfermium nuclei so far has been performed at the RITU separator, Jyväskylä (Finland) and the AMS, Argonne (USA) to investigate isotopes of nobelium [2,3,4] and fermium [3].

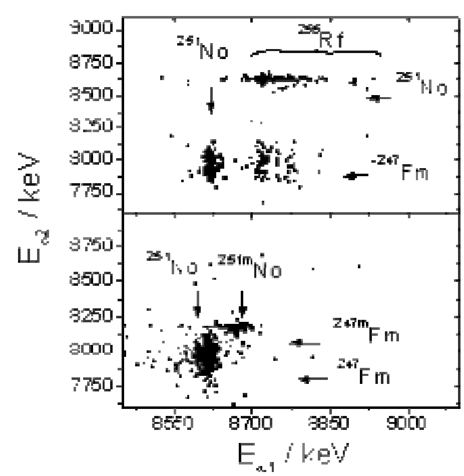
Most of the information on the nuclear structure of transfermium isotopes, however, has been obtained by means of decay spectroscopy. In most of the set-ups used presently [5,6] the isotopes of interest are separated in-flight from the projectile beam and are implanted into an arrangement of Si-detectors ('stop detector'), used to measure the α-decay energies. γ-rays emitted in coincidence to α-particles are measured with Ge-detectors mounted directly behind the Si-detectors, while CE may be measured in a 'box' of Si-detectors surrounding the 'stop detector'.

We will report here (part of) the results from recent nuclear structure investigations performed at SHIP (GSI Darmstadt). The isotopes ^{254,253}Lr, $^{251-253}$No, ^{246,247}Md have been produced in bombardments of ^{206,207}Pb, ^{209}Bi with ^{48}Ca or ^{209}Bi with ^{40}Ar projectiles. Their radioactive decays as well as those of their daughter products have been investigated by means of α- and α-γ-coincidence spectroscopy. Data analysis is still in progress, so the results have to be regarded as preliminary.

Experimental Results

Low Spin Isomeric States in Odd Mass Nuclei

Detailed investigation of the decay properties of transfermium nuclei in the vicinity of N=152 during the past years has shown that the occurrence of isomeric states decaying by α-emission with half-lives typically in the order of (0.1-10) s is a widespread phenomenon. According to Weisskopf estimations a spin difference of at least $\Delta I=3$ between the isomeric state and subjacent levels is necessary in order that α-emission can compete with internal transitions in the range of those half-lives. In principle, two combinations, low spin ground state - high spin isomeric state or high spin ground state – low spin isomeric state are possible. An example for the first possibility is ^{257}Rf, where an $11/2^-$[725] – isomeric state at E*=118 keV above the $1/2^+$[620] – ground state was identified [7]. More frequent, however, appear low spin isomeric states above high spin ground states. Isomeric states in ^{257}Db and ^{253}Lr [6] as well as a spontaneous fission activity of $T_{1/2}$=0.23 s observed in the reaction ^{40}Ar + ^{209}Bi and attributed to ^{247m}Md [8] had been interpreted in this way. In our recent irradiation of ^{209}Bi with ^{40}Ar an α-emitter of E_α=8785 keV with a half-life of $T_{1/2}$=(0.26 ±0.6) s was observed, representing the α-decay branch of ^{247m}Md. In back dated measurements α-decay from isomeric states, e.g. ^{257}Rf, ^{257}Db, ^{253}Lr, often was not recognized due half-lives similar to that of the ground state decay. Higher production rates, allowing more precise half-life measurements and resulting in higher numbers of α-α- correlations, thus giving observation or non-observation of (correlated) α-lines a higher statistical significance, have solved this problem in several cases (see above). In our recent experiments we confirmed α - decay from an isomeric stats in ^{255}Lr [9] and identified an isomeric state in ^{251}No ($T_{1/2}$=0.93 s). The corresponding α-line of E_α =8665 keV had been already reported by Ghiorso et al.[10], but was never observed within the α-decay chain of ^{255}Rf [6,7]. A direct production by ^{206}Pb(^{48}Ca,3n)^{251}No clearly showed in addition to the E_α=8610 keV – transition an α-line of 8665 keV, correlated to an α-decay of E_α=8170 keV, $T_{1/2}$=4.3 s (see fig. 1).The latter activity had already been observed in irradiations of ^{239}Pu with ^{12}C and was attributed to the decay of an isomeric state in ^{247}Fm [11].



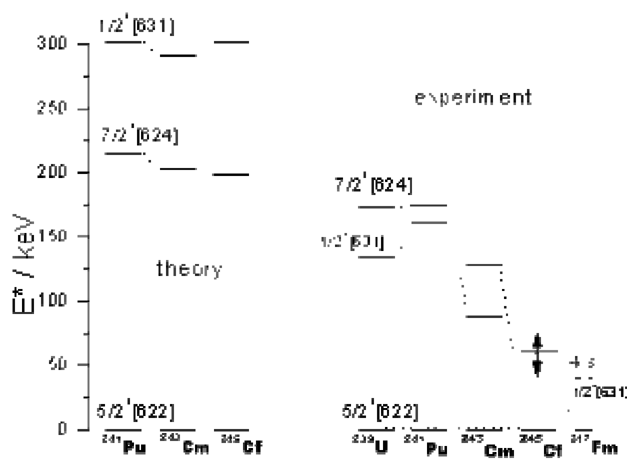


Figure 1. α-α correlation plot for a) evaporation residues produced in the reaction ^{50}Ti + ^{207}Pb at E = (4.77-4.86) AMeV, b) ^{48}Ca + ^{206}Pb at E = 4.81 AMeV.

Figure 2. Comparison of calculated [14] and experimental Nilsson levels of N=147 isotones.

Nilsson Levels in Odd Mass Even Z Nuclei

In even Z – isotopes similarities in α-decay properties and nuclear structure are known for isotonic odd mass nuclei. These correlations have been used to explain the α-spectra of ^{257,255}Rf, ^{253}No [6,7,12,13] and to construct partial level schemes for the daughter nuclei. The recent experiments at SHIP delivered enhanced decay data for ^{249}Fm, ^{251}No and thus allowed to extend such comparisons to the N=149 – isotones and their N=147 - decay products. Level predictions of Cwiok et al. [14] for the N=147 – isotones are compared with experimental results in Fig. 2. Cwiok et al. predict the 5/2$^+$[622] – Nilsson level as the ground-state of these nuclei, which is in line with the (older) experimental assignments, and rather stable excitation energies for the 7/2$^+$[624] – level, which is assigned to the ground-state of the N=149 – mother nuclei, and the 1/2$^+$[631] –level. Experimental assignments, however, place the 1/2$^+$[631] below the 7/2$^+$[624] – level and exhibit for both levels a drastic decrease of the energies from ^{241}Pu to ^{243}Cm [15].

In our experiments ^{249}Fm was produced by ^{207}Pb(^{48}Ca,2n) ^{253}No - α -> ^{249}Fm. Its α-line was significantly broader than that of ^{250}Fm, which was produced in the same irradiation by α-decay of ^{254}No. No γ-rays were observed in coincidence with α-decays of ^{249}Fm. Using the line width of ^{250}Fm, the ^{249}Fm, the α-spectrum was disentangled into two components of E_α=(7559±10) keV and E_α=(7583±10) keV. This line form was interpreted as due to energy summing of α-particles with conversion electrons either being stopped in the detector or leaving it. Taking into account that difference, maximum and minimum energy shifts of α-particles of $\Delta E_{max}=E^*-8$ keV and $\Delta E_{min}=21$ keV, as obtained from α-γ-coincidence measurements of ^{253}No, we obtain an excitation energy of the level populated by the α-decay of $E^*=(53\pm10)$ keV. Non-observation of γ-rays in coincidence with α-particles indicates that this value is already an upper limit. Respecting the number of observed α-decays and the efficiency of the Clover detector we obtain a lower limit for the conversion coefficient $\alpha_L > 50$, which refers to γ – energies $E_\gamma < 50$ keV for an M1 – transition [16].

For ^{251}No we observed a single narrow α-line of E_α=(8110 ± 10) keV (FWHM=21 keV). No γ – events in coincidence with α-particles were observed. Thus it is seemingly not influenced by energy summing K- or L- conversion electrons, which indicates that the 7/2$^+$[624] – level in ^{247}Fm is already located below the L-electron binding energy ($E^* < 20$ keV). The observation of an isomeric state ^{247m}Fm (1/2$^+$[631]) decaying by α-emission with a half-life of 3 s, however, suggests that the 7/2$^+$[624] – level already forms the ground state since a γ- decay life-time > 1s is rather expected for a ΔI=3 – transition (M3), than for a ΔI=2 – transition (E2) expected for 1/2$^+$[631] -> 5/2$^+$[622].

Nilsson Levels in Odd Mass Odd Z Nuclei

In odd Z nuclei similarities in α-decay properties and nuclear structure are known for isotopic odd mass nuclei. These correlations can be used to explain the α-spectra and to construct partial level schemes for the daughter nuclei. On the other hand, changes in the decay pattern may reveal a change of the ground state configuration of the daughter nuclei. Our investigations so far concentrated on the nuclei in the range Z=(99-105) characterised by T_z=45, 47, 49. Partial level schemes for these nuclides as derived on the basis of recent experiments at SHIP and literature data are shown in fig. 3.

The decay scheme of ^{257}Db has been discussed in detail in ref. [6]. Ground state was assigned as 9/2$^+$[624] as predicted by Cwiok [14], isomeric state as 1/2$^+$[521]. Isomeric decay populates an isomeric state in ^{253}Lr, decaying into 1/2$^-$ - state in ^{249}Md. Whether this state decays by α-emission is presently still unclear.

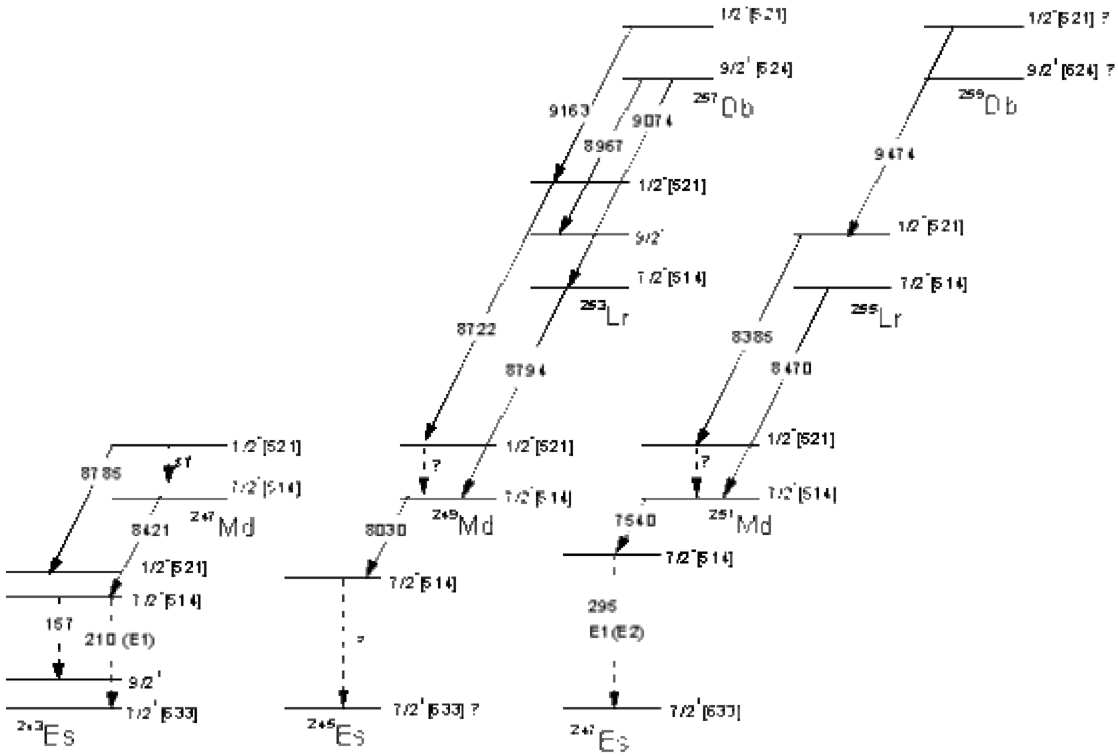


Figure 3. Adopted decay schemes for T_z=45, 47, 49 – odd Z isotopes. Level schemes and decay data are partly tentative and preliminary.

No statistically significant difference in α-decays of ^{249}Md following either ^{253m}Lr or ^{253}Lr have been observed so far. It was argued, however, that the decay pattern of ^{257m}Db and ^{257}Db exclude the $1/2^{-}$[521] Nilsson level as ground-state of ^{249}Md as predicted [14], but favour the $7/2^{-}$[514] level.

Similarities for the neighbouring T_z=49 – isotopes are evident. The two α-lines of ^{255}Lr are found to have different half-lives and thus represent the decay from different levels: ^{255m}Lr (E_α=8470 keV, $T_{1/2}$=2.1 s), ^{255}Lr (E_α=8375 keV, $T_{1/2}$=16.4 s). In analogy to the case of ^{253,253m}Lr the α-line of the higher energy has been attributed to the decay of the isomeric state. For the mother nucleus, ^{259}Db, only one α-lines has been reported so far [17]. The α-α-correlations observed by Gan et al. [17] suggest an assignment to an isomeric state similar to ^{257}Db. No statistically significant differences in the α-energy of ^{251}Md events following α - decays of either ^{255}Lr or ^{255m}Lr are observed. Also no γ-decays in coincidence with each of these lines were registered, while in coincidence with α-decays of ^{251}Md a 295.1 keV – γ-line as well as some Es-x-ray – events were observed. The ratio Σx-rays / $\Sigma\gamma$ suggest an E1-transition, which corroborates the ground-state level assignment $7/2^{-}$[514] and $7/2^{+}$[633] for ^{251}Md and ^{247}Es, respectively.

For the T_z=45 – members only α-decay of ^{247}Md and ^{243}Es was measured so far. The α-line at E_α 8421 keV was found in coincidence with a γ-line of 210 keV [12]. On the basis of coincidences with K-x-rays and an energy shift of the α-line due to energy summing with conversion electrons it was concluded that the γ-line represents rather an E1 – transition, which excludes a level assignment $3/2^{-}$[521] for the ground-state of ^{243}Es [18], but an E2 – transition, which would favour the latter assignment could not be excluded [12]. A repetition of this measurement clearly proved the E1 – character, suggesting $7/2^{+}$[633] as the ground-state level of ^{243}Es. In addition an α-γ – coincidence E_α=8471 keV – E_γ=157 keV was observed. It is tentatively assigned to γ-decay from the 7/2$^-$[514] – level into the first excited member of the ground state rotational band (9/2$^+$) of ^{243}Es.

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